Overview of Piano Key weir prototypes and scientific model investigations

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ABSTRACT: The interest in Piano Key weirs (PKW) was increasing over the past years, both in terms of application and hydraulic research. Several systematic model test series were performed and published so far, originating from different hydraulic laboratories around the world. Therein, the key geometric parameters dominating the hydraulic capacity of PKWs were identified as developed crest length, transversal weir width, height of the walls and key widths. The present paper compares the available data-sets provided by several laboratories and as constructed on prototypes, partially including a systematic model testing of the relevant parameters. The present overview is based on the geometrical dimensions of the investigated and designed PKWs, without giving any hydraulic examination.

1 INTRODUCTION

Piano Key weirs, representing an alternative to the traditional Labyrinth weirs, are used as efficient spillway inlet on dam rehabilitation projects (Leite Ribeiro et al. 2007, Laugier et al. 2009, Pinchard et al., 2011, Erpicum et al. 2011), as well as for new dam projects (Lempérière et al. 2011, Ho Ta Khanh 2011a). In addition to the increase in discharge capacity as compared to traditional Labyrinth weirs (Blancher et al. 2011, Anderson and Tullis 2011, 2012), PKWs have typically techno-economic advantages as: (i) minor impact on dam structure; (ii) minor or negligible impact on existing gates and other components, (iii) reliability of free surface overflow inlets, requiring little maintenance, (iv) low cost solution involving the construction of repeating concrete units (Lempériere and Ouamane, 2003; Laugier, 2007; Leite Ribeiro et al, 2009, Vermeulen et al; 2011), and (v) small sensitivity to debris accumulation (Pfister et al. 2013).

Compared to a linear weir, the efficiency of a PKW is mainly a consequence of its longer developed crest. However, with increasing upstream head, this advantage gets lost (Leite Ribeiro et al. 2012a, c, Machiels et al. 2011b, Ouamane and Lempérière 2006). As a consequence, PKWs are typically designed to operate under relative moderate heads, nevertheless resulting in a significant discharge capacity.

Given that many prototypes were erected in the past years, mainly designed using physical model studies, and as a consequence of several systematic research studies, including physical and numerical modeling, extensive hydraulic data related to hydraulic features of PKWs are today available. These contribute to the increase of comprehension regarding to the hydraulic behavior of PKWs. Nowadays, the key geometrical parameters influencing the hydraulic capacity of a PKW, namely the developed crest length, L, the transversal width W, the width of the inlet and outlet keys W_i and W_o, and the height of the inlet key P_i, were determined (Figure 1).

The discharge capacity of a PKW is affected influenced by further geometrical parameters, as the upstream approach flow channel conditions, the height and position of eventual parapet walls P_{px}, the crest shape, the shape of the upstream diffuser, the height of the foundation P_d, the up- and downstream overhang lengths B_o and B_i, and the tailwater conditions. However, the influence of these parameters can be considered as secondary in comparison with the influence of the key parameters as described above. Some attention has been recently directed to the thickness of the walls (Laugier et al. 2011). As PKWs typically operate under low heads, low values of the ratio H/T_s can decrease the discharge coefficient of the walls, then operating as broad-crested weirs instead of sharp-crested weirs.

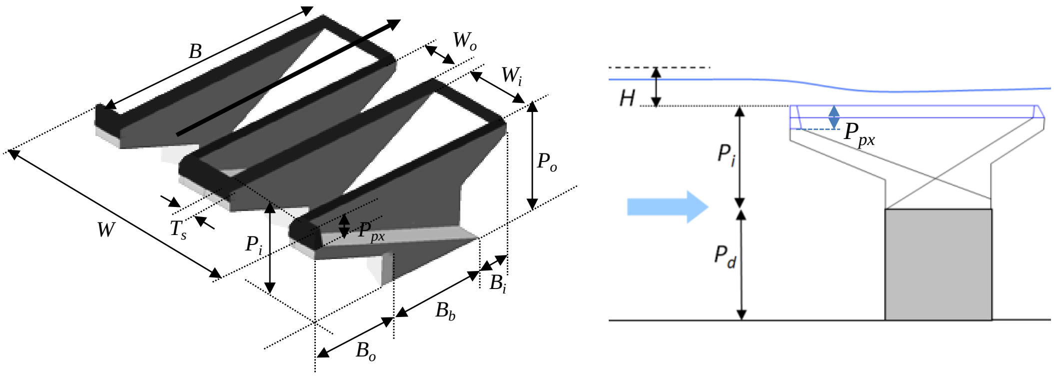

Figure 1. PKW Nomenclature according to Pralong et al. (2011).

The present paper assembles the – so far available – data-sets regarding PKW models tested in numerous laboratories under free overflow conditions (i.e., no submergence from the tailwater was observed). Both, scientific model investigations to systematically vary the dominant parameters (typically sectional models mounted in a tested in a linear channel) as well as prototype-related physical model investigations (typical full models with a reservoir as upstream condition) are considered. The aim of the paper is to summarize and interpret the geometry of the different PKW models already tested, and to compare these models to existing PKW prototypes, without giving a detailed hydraulic investigation. This comparison might be interesting to compare the outcome of the different investigations, and to find gaps for further research.

2 EXISTING DATABASES

2.1 *Prototype PKW*

Table 1 lists several built PKWs with their main hydraulic and geometrical characteristics. Data that were not accessible in literature are indicated with N/A.

The use of PKWs as a solution for dam rehabilitation has started in France, at EDF dams (Laugier 2007). Until 2013, five PKWs were built, namely at Goulours Dam, St-Marc Dam, Gloriettes Damand Etroit Dam (Vermeulen et al. 2011), and Malarce Dam. In addition, supplementary PKWs were tested in the frame of model investigations and will presumably be constructed in the next years (namely at Gage II Dam and Raviège Dam). In the EDF projects, the maximum design discharge over the PKWs is Q=525 m^3/s (Malarce Dam), which corresponds to a specific discharge (q=Q/W) equal to 12.3 m^2/s.

More recently, several PKWs were built, are under construction or planned in other countries, such as Algeria, Burkina Faso, India, Switzerland and Vietnam. For some cases, the design discharge exceeds Q=1000 m^3/s, reaching up to 8’700 m^3/s at Van Pongh Dam. The specific discharges are also considerable, reaching up to q=40 m^2/s at of Vinh Son 3 Dam.

PKWs are typically provided to operate under low heads, taking advantage of their overproportional developed crest length. As can be seen in Table 1, most of the PKWs have a ratio H_d/P_i around 0.3, where H_d is the upstream design head. Some exceptions are the PKWs of

Sawaa Khuddu Dam (India) and Ouldjet Mellegue Dam (Algeria), where H_d/P_i=0.56 and 0.66 respectively.

Table 1. Main hydraulic and geometrical characteristics of existing and planned PKWs.

Project	Country	Type	Q_d	q (Q_d/W)	H_d/P_i	L/W	P_i/W_i	W_i/W_o	S_i	P_i/T_s	P_{pxi}/P_i	Main reference
			[m^3/s]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	
Bambakari	Burkina Faso		1000	5.0	0.27	6.0	2.67	0.77	N/A	N/A	0.0	Lempérière et al. (2011)
Gage II Dam	France		400	11.8	0.25	7.8	3.75	1.23	0.67	15	0.0	Dugué et al. (2011)
Raviege Dam	France	B	400	10.4	0.32	6.8	2.08	1.50	0.51	13	0.2	Erpicum et al. (2011)
Malarce	France	A	525	12.3	0.34	8.1	2.67	1.04	0.64	22	0.4	Pinchard et al. (2011)
Goulours	France	A	68	5.7	0.31	4.9	1.15	1.80	0.53	16	0.0	Leite Ribeiro et al. (2009)
St-Marc	France	A	138	7.7	0.32	4.3	1.35	1.41	0.48	14	0.0	Leite Ribeiro et al. (2009)
Etroit	France	A	82	7.0	0.18	6.7	1.96	1.54	0.58	N/A	0.1	Leite Ribeiro et al. (2009)
Gloriettes	France	A	90	4.9	0.27	4.7	1.30	1.53	0.48	10	0.0	Leite Ribeiro et al. (2009)
Lhasi	India		115	1.0	0.13	6.0	2.17	1.25	N/A	N/A	0.0	Lempérière et al. (2011)
Van Pongh Dam	Vietnam	N/A	8700	28.9	N/A	5.8	2.09	1.19	N/A	22	N/A	Ho Ta Khanh et al (2011)
Dakmi 2	Vietnam	N/A	500	6.7	N/A	5.0	N/A	N/A	N/A	N/A	0.0	Ho Ta Khanh et al (2011)
Ngan Truoi	Vietnam	N/A	1560	16.3	N/A	5.0	2.04	1.35	N/A	16	N/A	Ho Ta Khanh et al (2011)
Vinh Son 3	Vietnam	N/A	4000	40.0	N/A	5.0	N/A	N/A	N/A	N/A	N/A	Ho Ta Khanh et al (2011)
Sawaa Kuddu	India	N/A	5240	38.0	0.56	4.9	1.33	1.00	N/A	N/A	0.0	Das Singhal and Sharma (2011)
Ouldjet Mellegue	Algeria		5240	0.7	0.66	4.8	N/A	1.37	N/A	N/A	N/A	Pfister et al. (2012)

2.2 *Scientific model PKW*

According to present literature, most of the systematic research PKW model studies were conducted in eight laboratories around the world. Table 2 lists the key research projects in the field of experimental PKW investigations. In total, almost 300 PKW model configurations were reported.

Table 2: Main current players of the PKW investigation.

Laboratory	Country	Number of PKW models	Main references
Laboratory of Hydraulic Developments and Environment Briska University	Algeria	83	Ouamane and Lempérière (2006) Ouamane (2011)
Ho Chi Minh City University of Technology (HCM)	Vietnam	5	Truong Chi Hien et al. (2006) HMC Internal reports
Water Resources Development & Management Department Indian Institute of Technology Roorkee	India	28	Das Singhal (2010)
Laboratory of Hydraulic Constructions Ecole Polytechnique Fédérale de Lausanne (LCH -EPFL)	Switzerland	50	Leite Ribeiro et al. (2011) Leite Ribeiro et al. (2012b)
National Hydraulic and Environment Laboratory Electricité de France (LNHE - EDF)	France	9	De Miranda (2011) Cicero and Delisle (2013)
Utah Water Research Laboratory Utah State University	USA	13	Anderson (2011)
Hydraulics in environmental and civil engineering Liège University (HECE - ULG)	Belgium	52	Machiels (2012)
Department of Civil Engineering Isfahan University of Technology	Iran	33	Kabiri-Samani and Javaheri (2012)

3 OVERVIEW AND COMPARISON

Table 3 gives an overview of the tested range of six dimensionless geometric parameters of so far tested PKWs, including all listed investigations, i.e., prototype PKWs as well as scientific models (being the sum of Tables 1 and 2). It can be seen that – with the exception of P_{pxi}/P_i, – all prototypes values were also studied in the scientific models. Or, in other words, the scientific investigations include larger limits than so far applied on prototypes.

Table 3: Limits of dimensionless geometrical ratios, comparison of scientific models with prototype PKWs.

		L/W	W_i/W_o	P_i/W_i	P_i/T_s	S_i	P_{pxi}/P_i
Scientific model	Maximum	8.5	2.45	4.71	300	2.00	0.43
	Minimum	2.5	0.00	0.59	5	0.25	0.00
Prototype	Maximum	8.1	1.80	3.75	22	0.67	0.38
	Minimum	4.3	0.77	1.15	10	0.48	0.00

The dominant dimensionless parameters influencing the discharge capacity of PKWs are the ratios L/W and H_d/P_i. For the experiments performed at EPFL (Leite Ribeiro et al. 2012c), exclusively these two terms are sufficient to predict the rating curve of all tested PKWs under all discharges with a maximum error of only ±17%. Herein, in order to focalize on the geometric parameters of the PKWs, the parameter H_d/P_i is not further considered. However, most of the scientific models include a test range of $0.1<H_d/P_i<3.0$, largely exceeding that of the prototypes (Table 1).

Hereafter, some dimensionless geometrical ratios of the numerous studies are visually compared.

Figure 2 plots P_i/W_i versus L/W for both, prototype and the scientific models. Generally, P_i/W_i increases in parallel with augmenting ratios L/W. This is explained with the fact that, for a given total PKW width W, an increase of the ratio L/W is typically linked to increasing the number of cycles and consequently decreasing the width of the inlet key W_i.

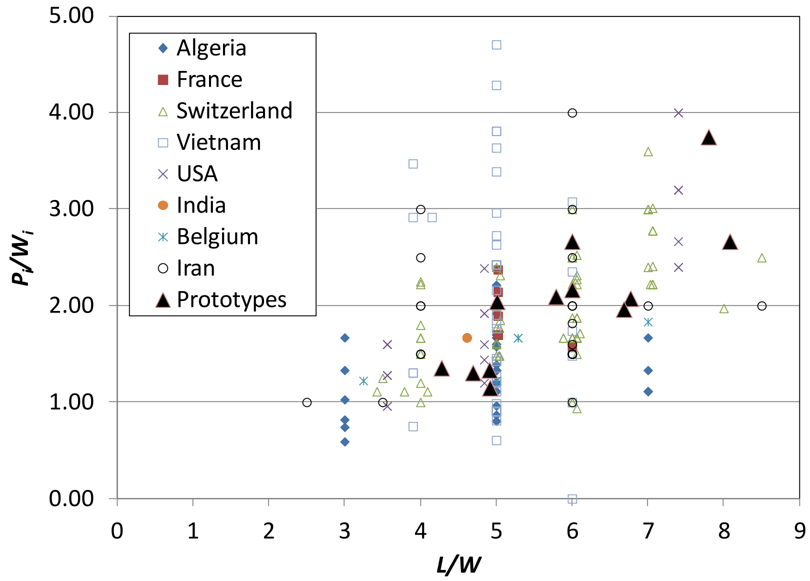

Figure 2. P_i/W_i as a function of L/W for all herein listed PKWs (Tables 1 and 2).

Another possibility to increase the ratio L/W is the augmentation of the streamwise PKW length B (particularly B_i and B_o). However, this impacts the slope S_i of the keys. According to Figure 3, this option was rarely exhausted, as most tests range around slopes of S_i=0.5 to almost 1.0 m/m.

Concerning the scientific model tests, the major part of them was conducted with slopes between S_i=0.3 and 1.0 m/m. Leite Ribeiro et al. (2011) have suggested that the influence of the slopes disappears when the upstream hydraulic head H_d is normalized with the height of the inlet key P_i for a range of slopes between 0.3 and 0.8. Results presented by Machiels (2012) and Machiels et al. (2011) mention an upper limit in around S_i=0.75.

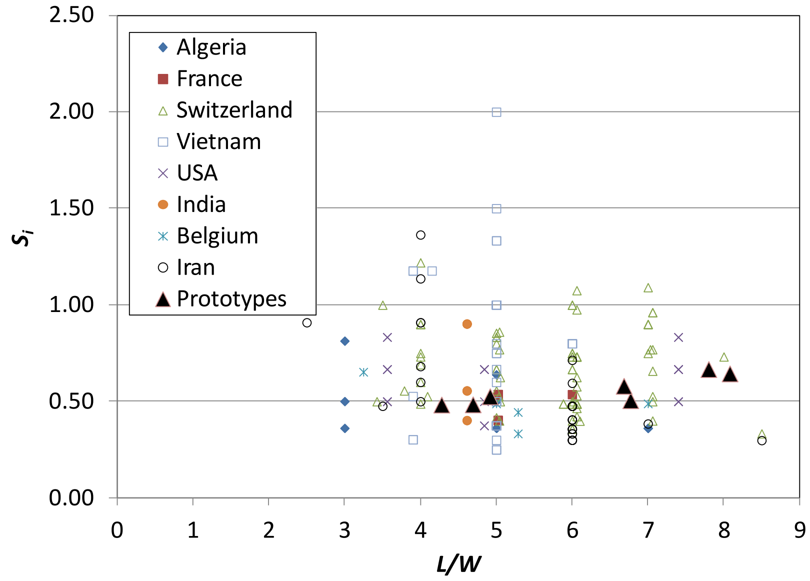

Figure 3. S_i as a function of L/W for all herein listed PKWs (Tables 1 and 2).

Although the ratio between the inlet and outlet key widths W_i/W_o is associated to the discharge efficiency of a PKW, its influence has been considered as secondary (Leite Ribeiro et al. 2012c). The scientific model tests varied this ration in large ranges to find optimal configurations (roughly between $2.5<W_i/W_o<0.5$), with a typical optimal value around $W_i/W_o=1.5$ (Leite Ribeiro 2012c, Machiels et al. 2010, Ouamane and Lempérière 2006).

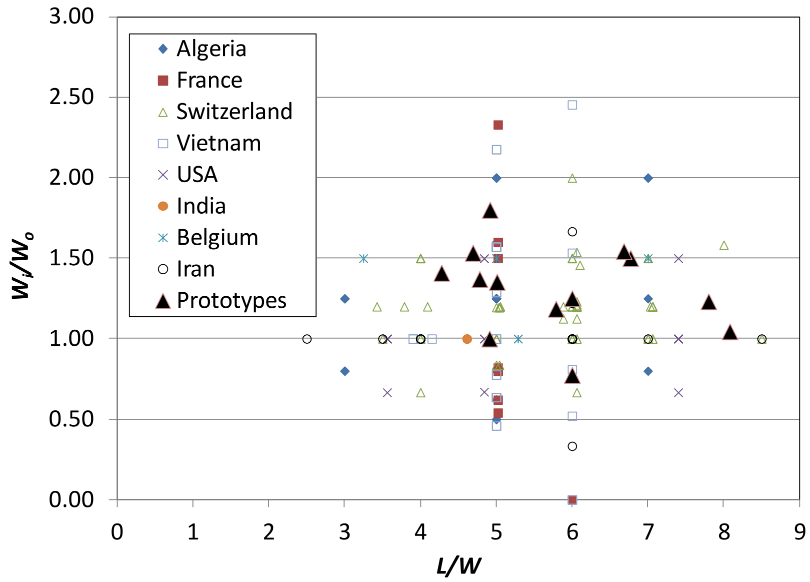

Figure 4. W_i/W_o as a function of L/W for all herein listed PKWs (Tables 1 and 2).

According to a 3D numerical study performed by Laugier et al. (2011), the thickness of the side walls has an important impact on the PKW discharge capacity (up to 20%), especially for low heads. For the existing PKW prototypes, the vertical walls of each key are made of reinforced concrete, with thickness between 0.2 and 0.3 m. Considering the height of the walls (P_i) as reference, it leads to ratios P_i/T_s between 10 and 22 for the existing PKWs. As shown in Figure 5, most of the scientific model tests were performed with P_i/T_s is in the range of those considered in the prototypes. As suggested by Laugier et al. (2011), the PKW discharge capacity may be increased by reducing the thickness of the walls and consequently increasing the ratio P_i/T_s. Such configurations were tested in Algeria and Iran.

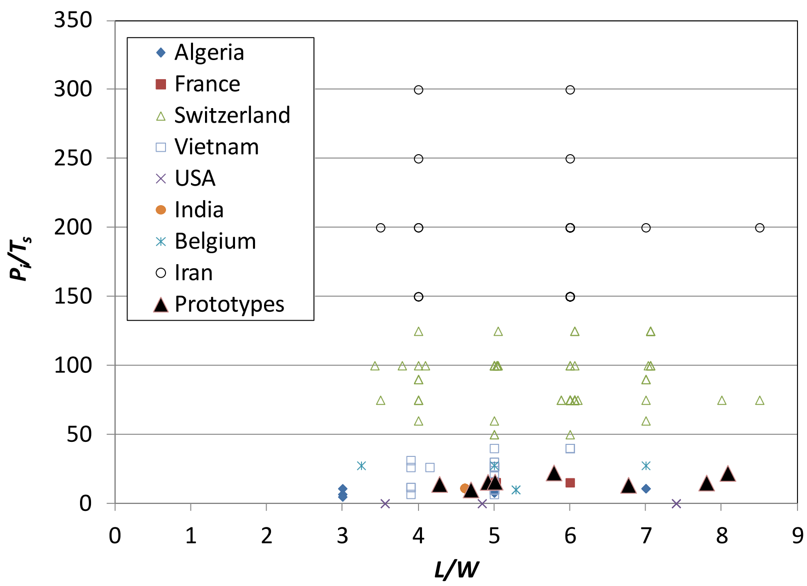

Figure 5. P_i/T_s as a function of P_i/W_i for all herein listed PKWs (Tables 1 and 2).

Until today, parapet walls were studied in three PKWs of EDF, namely at Etroit and Malarce Dams (built in both inlet and outlet keys) and in Raviège Dam (studied in both inlet and outlet keys and also in the outlet keys only). According to the results of Leite Ribeiro et al. (2012b) and Machiels et al. (online), the use of the parapet walls in the inlet key acts as an increase of the PKW height P_i. Therefore, the differences between the scientific tests performed in Switzerland, USA and Belgium and the two prototype models shown in Figure 6 are not important in terms of representativeness of the tests. However, as demonstrated by Leite Ribeiro et al. (2012b), parapet walls are efficient if applied in the outlet key.

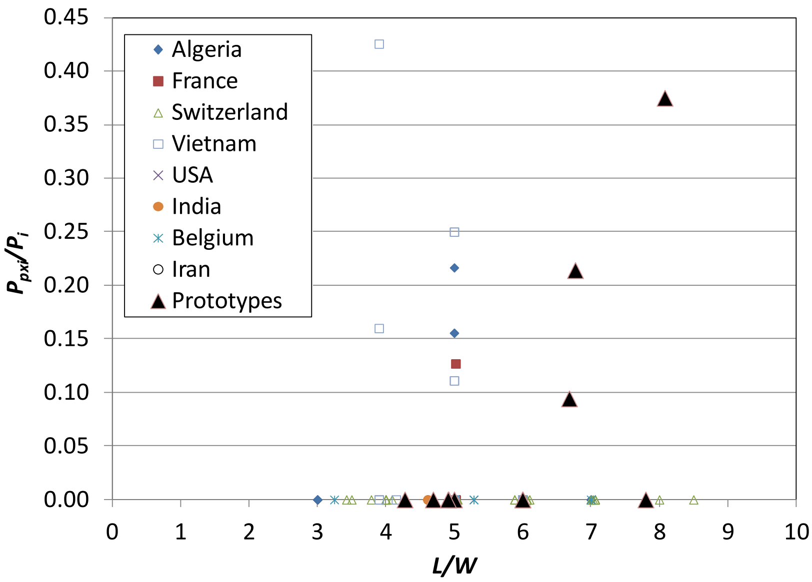

Figure 6. P_{pxi}/P_i as a function of L/W for all herein listed PKWs (Tables 1 and 2).

4 CONCLUSIONS

The present paper gives a rough overview on so far performed model tests related to PKW, including investigations related to specific prototypes as well as research models to conduct systemic parameter analyses.

The main outcomes are:

- The application of PKW as an alternative for dam rehabilitation and new spillway project increased during the last years. In parallel, an important database of systematic laboratory tests was created.
- The key parameters controlling the PKW discharge capacity are L, W, P_i and H. These have already been studied in detail by different authors based on systematic tests performed in laboratory channels.
- The studies in the next years regarding PKWs operating under free flow conditions will probably concentrate on the analysis of the influence of the secondary parameters, such as the approach conditions, the shape and the thickness of the crest, the shape of the deflectors below the outlet keys, the length of the overhangs, and the presence of parapets walls in the outlet key.

Nevertheless, one has to notice that the efficiency of PKWs in terms of their rating curve may be optimized thereby maximally by few percent. As compared to the uncertainty related to the derivation of the design flood, such an optimization process is to question.

ACKNOWLEDGEMENTS
The authors kindly thank Mr. Guy-Michel Cicero, EDF, France; Prof. Dr. Blake Tullis, Utah State University, USA; Prof. Ahmed Ouamane, University of Briska, Algeria; Mr. Ho Ta Khanh, EDF, France; Prof. Abdorreza Kabiri-Samani and Mr. Amir Javaheri, Isfahan University of Technology, Iran, for providing key limits of their model investigations.

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